

IMPROVEMENT OF MACHINABILITY AND SURFACE INTEGRITY DURING
ELECTRO DISCHARGE MACHINING OF INCONEL 718 USING NANO
POWDER SUSPENSION DIELECTRIC

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“This research is dedicated to my family especially to my mother, Halijah Samat and my late father, Ahmad Man, and to my beloved wife, Salbiah Omar and my kids, Mirza and Amani.”

Thank you for the support, encouragement and prayer.



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ABSTRACT

Inconel 718 is one of the most difficult to cut material due to its, high hardness, high toughness, and poor thermal conductivity results in heat concentrated in the cutting zone, making it ineffective to be processed through conventional machining. So usually, an electrical discharge machining (EDM) is chosen in order to overcome such limitations. However, EDM is known as a slow machining process. Thus, by employing powder suspension in the dielectric fluid it is believe to enhance the machining efficiency. To achieve high performance in EDM for this research, higher Peak current, I_p up to 40A, Pulse duration, t_{on} up to 400 μ s and Powder concentration, C_p up to 4g/l were selected as the main parameters. Copper (Cu) and Copper tungsten (CuW) were used as an electrode. Their influence on the machinabilities of the material removal rate (MRR), electrode wear rate (EWR), and surface roughness (R_a) were experimentally investigated. Some aspect of surface integrity, such as recast layer (R_L) and microhardness (MH) were also evaluated. The circulating dielectric system called High Performance EDM (HPEDM) was used when conducting the experiment incorporating powder suspension dielectric. The results have shown that, at a highest $I_p=40$ A and the lowest $t_{on}=200\mu$ s with $C_p=4$ g/l yields the highest MRR for both Cu and CuW electrodes. The improvement is about 32% and 50% for both electrodes when compared without powder concentration at the same parameter settings. Meanwhile, machining by using Cu electrode at $I_p = 40$ A, $t_{on} = 400\mu$ s and $C_p = 4$ g/l yields the lowest EWR respectively. For the CuW electrode, lowest value of EWR was obtained at $I_p=20$ A, $t_{on}=400\mu$ s and $C_p=0$ g/l. The lowest R_a when EDM machining by using Cu and CuW achieved at $I_p=20$ A, $C_p=0$ g/l and $t_{on}=400\mu$ s and 200 μ s, respectively. In the case of surface integrity, both electrode shows almost similar trend. The R_L thickness for both electrodes were increased with an increase of I_p , t_{on} and C_p . The MH on the R_L is much higher when compared to the base material. In the case of machinability, Cu electrode is the best option in EDM machining of Inconel 718.

ABSTRAK

Inconel 718 merupakan salah satu bahan yang paling sukar untuk dipotong kerana, mempunyai kekerasan dan ketahanan yang tinggi, serta sifat pengaliran haba yang rendah menyebabkan haba tertumpu di zon pemotongan, menjadikannya tidak begitu efektif untuk diproses melalui pemesinan konvensional. Jadi, mesin discaj elektrik (EDM) dipilih bagi mengatasi kekurangan tersebut. Namun, EDM dikenali sebagai proses pemesinan yang perlahan. Oleh itu, penggunaan penggantungan serbuk dalam dielektrik dipercayai mampu untuk meningkatkan kecekapan pemesinan. Untuk mencapai prestasi tinggi dalam pemesinan EDM bagi kajian ini, Arus puncak (I_p) yang tinggi sehingga 40A, Tempoh denyutan (t_{on}) sehingga 400 μ s dan Kepekatan serbuk (C_p) sehingga 4g/l telah dipilih sebagai parameter utama. Tembaga (Cu) dan Tembaga tungsten (CuW) digunakan sebagai elektrod. Kesan parameter-parameter tersebut terhadap kebolehmesanan melalui kadar pembuangan bahan (MRR), kadar kehausan elektrod (EWR), dan kekasaran permukaan (R_a) dikaji. Beberapa aspek integriti permukaan seperti lapisan putih (R_L), dan kekerasan mikro (MH) bahan kerja yang telah dimesin juga dinilai. Sistem aliran dielektrik yang dikenali sebagai *High Performance EDM* (HPEDM) digunakan untuk eksperimen yang melibatkan campuran serbuk. Keputusan menunjukkan bahawa pada I_p tertinggi 40A dan t_{on} paling rendah 200 μ s serta C_p tertinggi 4g/l menghasilkan MRR tertinggi untuk elektrod Cu dan CuW. Peningkatan kira-kira 32% dan 50% untuk setiap elektrod berbanding tanpa kepekatan serbuk pada tetapan parameter yang sama. Sementara itu, pemesinan dengan menggunakan elektrod Cu pada $I_p=40$ A, $t_{on}=400\mu$ s dan $C_p=4$ g/l menghasilkan EWR yang paling rendah. Manakala nilai terendah EWR untuk elektrod CuW direkodkan pada $I_p=20$ A, $t_{on}=400\mu$ s dan $C_p=0$ g/l. R_a terendah apabila melakukan pemesinan EDM dengan menggunakan Cu dan CuW masing-masing dicapai pada $I_p=20$ A, $C_p=0$ g/l dan $t_{on}=400\mu$ s dan 200 μ s. Secara keseluruhannya, ketebalan R_L didapati meningkat dengan peningkatan I_p , t_{on} dan C_p . MH pada R_L jauh lebih tinggi berbanding dengan material utama. Dari segi kebolehmesanan, elektrod Cu adalah pilihan terbaik untuk pemesinan EDM bagi Inconel 718.

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LIST OF ABBREVIATIONS AND SYMBOLS

Al	-	Aluminium
C_p	-	Powder concentration
Cu	-	Copper
CuW	-	Copper Tungsten
EDM	-	Electro discharge machining
EWR	-	Electrode wear rate
MH	-	Micro-hardness
HAZ	-	Heat affected zone
HPEDM	-	High performance electrical discharge machining
HRC	-	Rockwell hardness unit
HV	-	Vickers hardness unit
I_p	-	Peak current
MRR	-	Material removal rate
OM	-	Optical microscope
PLC	-	Programmable Logic Controller
PM	-	Powder Metallurgy
PS EDM	-	Powder suspension electrical discharge machining
R_a	-	Surface roughness
R_L	-	Recast layer
SA	-	Surface area
SEM	-	Scanning electron microscopy
SI	-	Surface integrity
SiC	-	Silicon Carbide
t_m	-	Machining times

REFERENCES

- Abbas, N. M., Solomon, D. G., and Bahari M. F. (2007). A review on current research trends in electrical discharge machining (EDM). *International Journal of Machine Tools and Manufacture* 47(7–8): pp.1214-1228.
- Agie Charmilles Group (2005). *EDM for machining hard metals*. Retrieved May. 14th 2015. From <https://www.georgfischer.com/content/dam/gfac/PDF-Documents/sales/USA/Literature/Archived-Literature/HARD METALS .pdf>
- Amorim, F. L., and Weingaertner, W. L. (2004). Die-Sinking Electrical Discharge Machining of a High-Strength Copper- Based Alloy for Injection Molds. *Journal of the Brazilian Society of Mechanical Sciences and Engineering*. Vol. XXVI(2), pp. 137-144.
- Benedict, G. F. (1987). *Nontraditional Machining processes*. Marcel Dekker, INC. New York. pp. 207.
- Beri, N., Maheshwari, S., Sharma, C., and Kumar, A. (2014). Surface quality modification using powder metallurgy processed CuW electrode during electrical discharge machining of Inconel 718. *Procedia Material Science* Vol. 2(3), pp. 167-171.
- Beri, N., Maheshwari, S., Sharma, C., and Kumar, A. (2008). Performance Evaluation of Powder Metallurgy Electrode in Electrical Discharge Machining of AISI D2 Steel Using Taguchi Method. *International Journal of Aerospace and Mechanical Engineering* Vol 5, pp. 2629-2634.

Beri, N., Maheshwari, S., Sharma, C., and Kumar, A. (2010). Technological Advancement in Electrical Discharge Machining with Powder Metallurgy Processed Electrodes: A Review. *Materials and Manufacturing Processes Vol. 25*, pp. 1186-1197.

Beri, N., Pungotra, H., and Kumar, A. (2012). To Study the Effect of Polarity and Current during Electric Discharge Machining of Inconel 718 with CuW Powder Metallurgy Electrode. *Proceedings of the National Conference on Trends and Advances in Mechanical Engineering, YMCA University of Science & Technology, Faridabad, Haryana.*, pp. 476-481.

Bharti, P. S., Maheshwari, S., and Sharma, C. (2010). Experimental Investigation Of Inconel 718 During Die-Sinking Electric Discharge Machining." *International Journal of Engineering Science and Technology Vol. 2(11)*, pp. 6464-6473.

Bhattacharya, A., Batish, A., Singh, G., and Singla, V. (2011). Optimal parameter settings for rough and finish machining of die steels in powder-mixed EDM. *International Journal of Advanced Manufacturing Technology*. pp. 1-12.

Bhattacharya, A., Batish, A., and Kumar, N. (2013). Surface characterization and material migration during surface modification of die steels with silicon, graphite and tungsten powder in EDM process. *Journal of mechanical Science and Technology*. Vol. 27(1), pp. 133-140.

Bibus Metals Ag (2007). *Inconel[®] Alloy 718*. Retrieved on June 24th 2013. From http://www.bibusmetals.ch/fileadmin/materials/PDF/Inconel_718.pdf

Brian P., (2013). *Familiar With Your EDM Fluid? Fluid choice and maintenance affect part quality, reduce DC arcing*. Retrieved April 3rd 2015 from <http://www.cimindustry.com/article/metalworking/familiar-with-your-edm-fluidr>

- Chow, H. M., Yan, B. H., Huang, F. Y., and Hung, J. C. (2000). Study of added powder in kerosene for the micro-slit machining of titanium alloy using electro-discharge machining. *Journal of Materials Processing Technology* Vol. 101(1–3), pp. 95-103.
- Chow, H. M., Yang, L. D., Lin, C. T., and Chen, Y. F. (2008). The use of SiC powder in water as dielectric for micro-slit EDM machining. *Journal of Materials Processing Technology* Vol. 195(1–3), pp. 160-170.
- DeGarmo, E. P., Black, J. T., and Kohsel, R. A. (2003). *Materials and process in manufacturing*. 9th edition. John Wiley and Son, Inc. USA.
- Dudzinski, D., Devillez, A., Moufki, A., Larrouquère, D., Zerrouki, V., and Vigneau, J. (2004). A review of developments towards dry and high speed machining of Inconel 718 alloy. *International Journal of Machine Tools and Manufacture* Vol. 44(4), pp. 439-456.
- El-Hofy, H. (2007). *Fundamentals of Machining Processes: Conventional and Nonconventional Processes*. Taylor & Francis Group. Boca Raton, FL. pp. 371-385.
- Ezugwu, E. O. (2005). Key improvements in the machining of difficult-to-cut aerospace superalloys. *International Journal of Machine Tools & Manufacture* Vol. 45, pp. 1353-1367.
- Fenggou, C., and Dayong, Y. (2004). The study of high efficiency and intelligent optimization system in EDM sinking process. *Journal of Materials Processing Technology* Vol. 149(1-3), pp. 83-87.
- Fonda, P., Wang, Z., Yamazaki, K., and Akutsu, Y. (2008). A fundamental study on Ti-6Al-4V's thermal and electrical properties and their relation to EDM



PTTA UTHM
PERPUSTAKAAN TUN ABU AMINAH

productivity. *Journal of Materials Processing Technology* Vol. 202(1-3), pp. 583-589.

Ghewade, D. V., and Nipanikar, S. R. (2011). Experimental Study of Electro Discharge Machining for Inconel Material. *Journal of Engineering Research and Studies* Vol. II(II/April-June,2011), pp. 107-112.

Ghoreishi, M., and Atkinson, J. (2002). A comparative experimental study of machining characteristics in vibratory. *Journal of Materials Processing Technology*. Vol 120, pp. 374–384.

Gostimirovic, M., Kovac, P., Skoric, B., and Sekulic, M. (2012). Effect of electrical pulse parameters on the machining performance in EDM. *Indian Journal of Engineering & Materials Sciences* Vol. 18(December 2012), pp. 411-415.

Guitrau, E. B. (1997). *The Edm Handbook*. Hanser Gardner Publication, Cincinnati. pp. 19-26.

Guu Y.H. (2005). AFM surface imaging of AISI D2 tool steel machined by the EDM process, *Applied Surface Science* Vol.242, pp.245–250.

Hamidi, A. G., Arabi, H., and Rastegari, S. (2011). A feasibility study of W-Cu composites production by high pressure compression of tungsten powder. *International Journal of Refractory Metals and Hard Materials* Vol. 29(1), pp. 123-127.

Han, F., Wang, Y., and Zhou, M. (2009). High-speed EDM milling with moving electric arcs. *International Journal of Machine Tools and Manufacture* Vol. 49(1), pp. 20-24.

Hascallk, A., and Caydas, U. (2007). Electrical discharge machining of titanium alloy (Ti-6Al-4V). *Applied Surface Science* Vol. 253(22), pp. 9007-9016.



PTTA UTM
PERPUSTAKAAN TUN AMINAH

- Hewidy, M. S., El-Taweel, T. A., and El-Safty, M. F. (2005). Modelling the machining parameters of wire electrical discharge machining of Inconel 601 using RSM. *Journal of Materials Processing Technology Vol. 169(2)*, pp. 328-336.
- Ho, K. H., and Newman, S. T. (2003). State of the art electrical discharge machining (EDM). *International Journal of Machine Tools and Manufacture Vol. 43(13)*, pp. 1287-1300.
- Ho, S. K., Aspinwall, D. K., and Voice, W. (2007). Use of powder metallurgy (PM) compacted electrodes for electrical discharge surface alloying/modification of Ti-6Al-4V alloy. *Journal of Materials Processing Technology Vol. 191(1-3)*, pp. 123-126.
- Hsieh, M. F., Tung, C. J., Yao, W. S., Wu, M. C., and Liao, Y. S. (2007). Servo design of a vertical axis drive using dual linear motors for high speed electric discharge machining. *International Journal of Machine Tools and Manufacture Vol. 47(3-4)*, pp. 546-554.
- Hsue, A. W. J., and Chih, H. C. (2009). Control strategy for high speed electrical discharge machining (die-sinking EDM) equipped with linear motors. *Advanced Intelligent Mechatronics, 2009. AIM 2009. IEEE/ASME*
- Jacobs, J. A., and Kilduff, T. F. (2005). "Engineering Materials Technology: Structure, Processing, Properties, and Selection. 5th edition. Prentice Hall, New Jersey." Vol., pp. 369-372.
- Jahan, M., Rahman, M., and Wong, Y. (2011). Study on the nano-powder-mixed sinking and milling micro-EDM of WC-Co. *International Journal of Advanced Manufacturing Technology Vol. 53(1)*, pp. 167-180.



PTT AUTHM
PERPUSTAKAAN TUNKU TUN AMINAH

- Jahan, M. P., Wong, Y. S., and Rahman, M. (2009). A study on the fine-finish die-sinking micro-EDM of tungsten carbide using different electrode materials. *Journal of Materials Processing Technology* Vol. 209, pp. 3956-3967.
- Janmanee, P., and Muttamara, A. (2010). Performance of Difference Electrode Materials in Electrical Discharge Machining of Tungsten Carbide. *Energy Research Journal* Vol. 1(2), pp. 87-90.
- Kalpakjian, S., and Schmid, S. R. (2008). *Manufacturing Processes for Engineering Materials*. 5th edition in SI Units. Prentice Hall, Jurong, Singapore. pp. 561-563.
- Kaminski, P. C., and Capuano, M. N. (2003). Micro hole machining by conventional penetration electrical discharge machine. *International Journal of Machine Tools and Manufacture* Vol. 43(11), pp. 1143-1149.
- Kang, S., and Kim, D. (2003). Investigation of EDM characteristics of nickel-based heat resistant alloy. *Journal of Mechanical Science and Technology*. Vol.17(10),pp. 1475-1484.
- Kansal, H. K., Singh, S., and Kumar, P. (2005). Parametric optimization of powder mixed electrical discharge machining by response surface methodology. *Journal of Materials Processing Technology* Vol. 169(3), pp. 427-436.
- Kansal, H. K., Singh, S., and Kumar, P. (2007). Technology and research developments in powder mixed electric discharge machining (PMEDM). *Journal of Materials Processing Technology* Vol. 184(1-3), pp. 32-41.
- Karastojkovic and Janjusevic (2003). Hardness and structure changes at surface in Electrical Discharge Machined steel 3840. *Proceedings of 3rd BMC-2003-Ohrid, R. Macedonia*.



PERPUSTAKAAN TUNKU TUN AMINAH

- Kern, R. (2008). *TechTips: Sinker Electrode Material Selection*. EDM, Today. July/August 2008 Issue.
- Kern, R. (2009). *TechTips: Sinker Dielectric Fundamentals*. EDM, Today. January/February 2009 Issue.
- Klocke, F., Schwade, M., Klink, A., and Veselovac, D. (2013). Analysis of Material Removal Rate and Electrode Wear in Sinking EDM Roughing Strategies using Different Graphite Grades. *Procedia CIRP Vol 6*, pp.163 – 167
- Klocke, F., Lung, D., Antonoglou, G., and Thomaidis, D. (2004). The effects of powder suspended dielectrics on the thermal influenced zone by electrodischarge machining with small discharge energies. *Journal of Materials Processing Technology Vol. 149(1–3)*, pp. 191-197.
- Kocher, G., Chopra, K., and Kumar, S. (2012). Investigation of Surface integrity of AISI D3 tool steel After EDM. *International Journal of Emerging Technology and Advanced Engineering Vol. 2(4)*, pp. 160-162.
- Kumar, A., Maheshwari, S., Sharma, C., and Beri, N. (2010). Realizing Potential of Graphite Powder in Enhancing Machining Rate in AEDM of Nickel Based Super Alloy 718. *Proceeding of. International Conference on Advances in Mechanical Engineering 2010*, pp. 50-53.
- Kumar, A., Maheshwari, S., Sharma, C., and Beri, N. (2011). Analysis of Machining Characteristics in Additive Mixed Electric Discharge Machining of Nickel-Based Super Alloy Inconel 718. *Materials and Manufacturing Processes Vol. 26(8)*, pp. 1011-1018.
- Kumar, V., Beri, N., Kumar, A., and Singh, P. (2010). Some Studies On Electrical Discharge Machining of Hastelloy Using Powder Metallurgy Electrode.

International Journal of Advanced Engineering Technology Vol. I(II/July-Sept.,2010), pp. 16-27.

Kung, K.Y., Horng J.T., and Chiang, K.T., (2009). Material removal rate and electrode wear ratio study on the powder mixed electrical discharge machining of cobalt-bonded tungsten carbide. *International Journal of Advanced Manufacturing Technology Vol. 40(1-2), pp.95–104.*

Kuppan, P., Rajadurai, A., and Narayanan, S. (2008). Influence of EDM process parameters in deep hole drilling of Inconel 718. *International Journal Advanced Manufacturing Technology Vol. 38, pp. 74-84.*

Lajis, M. A., Radzi, H. C. D. M., and Amin, A. K. M. N. (2009). The Implementation of Taguchi Method on EDM Process of Tungsten Carbide. *European Journal of Scientific Research Vol. 26(4), pp. 609-617.*

Lee, H. T., Hsu, F. C., and Tai, T. Y. (2004). Study of surface integrity using the small area EDM process with a copper-tungsten electrode. *Materials Science and Engineering: A Vol. 364(1–2), pp. 346-356.*

Lee, S. H., and Li, X. (2003). Study of the surface integrity of the machined workpiece in the EDM of tungsten carbide. *Journal of Materials Processing Technology Vol. 139(1–3), pp. 315-321.*

Lee, S. H., and Li, X. P. (2001). Study of the effect of machining parameters on the machining characteristics in electrical discharge machining of tungsten carbide. *Journal of Materials Processing Technology Vol. 115(3):pp. 344-358.*

Li, L., Wong, Y. S., Fuh, J. Y. H., and Lu, L. (2001). Effect of TiC in copper-tungsten electrodes on EDM performance. *Journal of Materials Processing Technology Vol. 113(1-3), pp. 563-567.*

- Li, L., Guo, Y.B., Wei, X.T., and Li, W., (2013). Surface integrity characteristics in wire-EDM of Inconel 718 at different discharge energy. *Procedia CIRP* 6: 221-226
- Liqing, L., and Yingjie, S. (2013). Study of Dry EDM with Oxygen-Mixed and Cryogenic Cooling Approaches. *Procedia CIRP* 6(0): 344-350.
- Makino (2015). *Process Insights – Advances in EDM for Aerospace*. Retrieved August 13th 2015. From www.radical-departures.net/articles/advances-in-edm-for-aerospace/
- Marafona, J. (2009). Black layer affects the thermal conductivity of the surface of copper–tungsten electrode. *International Journal of Advanced Manufacturing Technology* Vol. 42(5), pp. 482-488.
- Marafona, J., and Wykes, C. (2000). A new method of optimising material removal rate using EDM with copper–tungsten electrodes. *International Journal of Machine Tools and Manufacture* Vol. 40(2), pp. 153-164.
- McGeough, J. A. (1988). *Advanced Methods of Machining*. Chapman and Hall Ltd, London. pp. 128-1147.
- Ming, Q. Y., and He, L. Y. (1995). Powder-suspension dielectric fluid for EDM. *Journal of Materials Processing Technology* Vol. 52(1), pp. 44-54.
- Murthy, V. S. R., and Philips, P. K. (1987). Pulse train analysis in ultrasonic assisted EDM. *International Journal of Machine Tools & Manufacture* Vol. 27(4), pp. 469-477.
- Newton, T. R., Melkote, S. N., Watkins, T. R., Trejo, R. M., and Reister, L. (2009). Investigation of the effect of process parameters on the formation and



PTT AUTHM
PERPUSTAKAAN TUN ABULRAZAK

characteristics of recast layer in wire-EDM of Inconel 718. *Materials Science and Engineering Vol. 513-514(0)*, pp. 208-215.

Pandey, A., and Singh, S. (2010). Current research trends in variants of Electrical Discharge Machining: A review. *International Journal of Engineering Science and Technology Vol. 2(6)*, pp. 2172-2191.

Patel, K. M., Pandey, P. M., and Venkateswara, R. P. (2009). Surface integrity and material removal mechanisms associated with the EDM of Al₂O₃ ceramic composite. *International Journal of Refractory Metals and Hard Materials Vol. 27(5)*, pp. 892-899.

Payal, H. S., Choudhary, R., and Singh, S. (2008). Analysis of electro discharge machined surfaces of EN-31 tool steel. *Journal of Scientific & Industrial Research Vol. 67(December 2008)*, pp.1072-1077.

Peças, P., and Henriques, E. (2003). Influence of silicon powder-mixed dielectric on conventional electrical discharge machining. *International Journal of Machine Tools and Manufacture Vol. 43(14)*, pp. 1465-1471.

Peças, P., and Henriques, E. (2008). Effect of the powder concentration and dielectric flow in the surface morphology in electrical discharge machining with powder-mixed dielectric (PMD-EDM). *International Journal of Advanced Manufacturing Technology Vol. 37(11)*, pp. 1120-1132.

Prihandana, G., Mahardika, M., Hamdi, M., Wong, Y., and Mitsui, K. (2011). Accuracy improvement in nanographite powder-suspended dielectric fluid for micro-electrical discharge machining processes. *The International Journal of Advanced Manufacturing Technology Vol. 56(1)*, pp. 143-149.



PT TAA UT HM
PERPUSTAKAAN TUNJUNING AMINAH

- Prihandana, G. S., Mahardika, M., Hamdi, M., and Mitsui, K. (2009). The Current Methods for Improving Electrical Discharge Machining Processes. *Recent Patents on Mechanical Engineering 2009 Vol. (2)*, pp. 61-68.
- Rahman, M. M., Khan, M. A. R., Kadirgama, K., Noor, M. M., and Bakar, R. A. (2010). Modeling of Material Removal on Machining of Ti-6Al-4V through EDM using Copper Tungsten Electrode and Positive Polarity. *World Academy of Science, Engineering and Technology Vol. 71*.
- Rajesha, S., Sharma, A., and Kumar, P. (2010). Some aspects of surface integrity study of electro discharge machined Inconel 718. *Proceeding of the 36th International Matador Conference*, pp. 439-444.
- Rajesha, S., Sharma, A., and Kumar, P. (2011). On Electro Discharge Machining of Inconel 718 with Hollow Tool. *Journal of Materials Engineering and Performance*, pp. 1-10.
- Rajurkar, K. P., and Wang, W. M. (1996). *A Spark of Intelligence*. April 1996/Volume 48(3). Retrieved on May 15 2012. From <http://www.ctemag.com/dynamic.articles.php?id=169>
- Rao, P. N. (2009). *Manufacturing Technology: Metal Cutting and Machine Tools* 2nd Edition. McGraw Hill, New Delhi." Vol. 2, pp. 296-297.
- Sam A. (2000). *The case for additive technology in EDM*. *Modern Machine Shop*. Retrieved July 3rd 2012. From <http://www.mmsonline.com/articles/the-case-for-additive-technology-in-edm>
- Sharma, S., Kumar, A., and Beri, N. (2011). Study of tool wear rate during powder Mixed EDM of hastelloy steel. *International Journal of Advanced Engineering Technology Vol. II(II/April-June, 2011)*, pp. 133-139.

- Sharma, S., Kumar, A., Beri, N., and Kumar, D. (2010). Effect of Aluminium Powder Addition in Dielectric During Electric Discharge Machining of Hastelloy on Machining Performance Using Reverse Polarity. *International Journal of Advanced Engineering Technology Vol. I(III/Oct.-Dec.,2010)*, pp. 13-24.
- Singh, P., Kumar, A., Beri, N., and Kumar, V. (2010). Some Experimental Investigation On Aluminium Powder Mixed EDM On Machining Performance of Hastelloy Steel. *International Journal of Advanced Engineering Technology Vol. I(Issue II/July-Sept.2010)*, pp. 28-45.
- Singh, S., and Bhardwaj, A. (2011). Review to EDM by Using Water and Powder-Mixed Dielectric Fluid. *Journal of Minerals & Materials Characterization & Engineering Vol. 10(2)*, pp. 199-230.
- Singh, S., Maheshwari, S. and Pandey, P. C. (2004). Some investigations into the electric discharge machining of hardened tool steel using different electrode materials. *Journal of Materials Processing Technology Vol. 149(1-3)*, pp. 272-277.
- Small, K. B., Englehart, D. A., and Christman, T. A. (2008). *A Guide to Etching Specialty Alloys for Microstructural Evaluation*. Carpenter Technology Corp., Wyomissing, PA, USA. Retrieved May 26th 2012. From <http://www.carttech.com/news.aspx?id=578>.
- Sommer, C. (2009). *Non-Traditional Machining Machining Handbook*. Advance Publishing Inc, Houston. Texas. pp. 117-158.
- Son, S., Lim, H., Kumar, A. S., and Rahman, M. (2007). Influences of pulsed power condition on the machining properties in micro EDM. *Journal of Materials Processing Technology Vol. 190(1-3)*, pp. 73-76.



PTT AUTHM
PERPUSTAKAAN TUNKU TUN AMINAH

- Sudhakara, D., Naik, B. V., and Sreenivasulu, B. (2012). The experimental analysis of surface characteristics of Inconel-718 using electrical discharge machining. *International Journal and Mechanical Engineering and Robotic Research*. Vol. 1(3), pp.371-388.
- Syed, K.H., and Kuppan, P., (2012). Performance of electrical discharge machining using aluminium powder suspended distilled water, *Turkish Journal of Engineering and Environmental Science*, vol. 36, pp. 195-207.
- Theisen, W., and Schuermann, A. (2004). Electro discharge machining of nickel–titanium shape memory alloys. *Materials Science and Engineering Vol. A* 378(2004), pp. 200–204.
- Thoe, T.H., Aspinwall, D.K., and Killey, N. (1999). Combined ultrasonic and electrical discharge machining of ceramic coated nickel alloy. *Journal of Materials Processing Technology* 92–93, pp.323–328.
- Tsai, H. C., Yan, B. H., and Huang, F. Y. (2003). EDM performance of Cr/Cu-based composite electrodes. *International Journal of Machine Tools and Manufacture* Vol. 43(3), pp. 245-252.
- Tsutsui, T. (2012). Recent Technology of Powder Metallurgy and Applications. *Hitachi Chemical Technical Report Vol. No. 54*.
- Tzeng, Y. F., and Chen, F. C. (2005). Investigation into some surface characteristics of electrical discharge machined SKD-11 using powder-suspension dielectric oil. *Journal of Materials Processing Technology* Vol. 170(1–2), pp. 385-391.
- Tzeng, Y.F. (2008). Development of a flexible high-speed EDM technology with geometrical transform optimization. *Journal of Materials Processing Technology* Vol. 203(1–3), pp. 355-364.



- Tzeng, Y.F., and Chen, F.C. (2007). Multi-objective optimisation of high-speed electrical discharge machining process using a Taguchi fuzzy-based approach. *Materials & Design Vol. 28(4)*, pp. 1159-1168.
- Ulutan, D., and Ozel, T. (2011). Machining induced surface integrity in titanium and nickel alloys: A review. *International Journal of Machine Tools and Manufacture Vol. 51(3)*, pp. 250-280.
- USA Special Metals Corporation (2007), *Inconel alloy 718*, Retrieved May 14th 2013. From [http://www.specialmetals.com/documents/Inconel alloy 718.pdf](http://www.specialmetals.com/documents/Inconel%20alloy%20718.pdf)
- Wang, W. F. (1998). Effect of tungsten particle size and copper content on electrodischarge electrodes. *Metal Powder Report Vol. 53(11)*, pp. 38-38.
- Wong, Y. S., Lim, L. C., Rahuman, I., and Tee, W. M. (1998). Near-mirror-finish phenomenon in EDM using powder-mixed dielectric. *Journal of Materials Processing Technology Vol. 79(1-3)*, pp. 30-40.
- Yeo, S. H., and Tan, L. K. (1999) Effects of ultrasonic vibrations in micro electro-discharge machining. *Journal of Micromechanics and Microengineering 9*, pp. 345-352.
- Yilmaz, O., and Okka, M. (2010). Effect of single and multi-channel electrodes application on EDM fast hole drilling performance. *The International Journal of Advanced Manufacturing Technology Vol. 51(1)*, pp. 185-194.
- Youssef, H. A., and El-Hofy, H. (2008). *Machining Technology: Machine Tools and Operations*. CRC Press, Taylor & Francis Group. Boca Raton, FL. pp. 464.
- Yu, Z. B., Jun, T., and Masanori, K. (2004). Masanori, Dry electrical discharge machining of cemented carbide. *Journal of Materials Processing Technology Vol 149*, pp. 353-357.



PTT AUTHM
PERPUSTAKAAN TUNKU TUN AMINAH

Zaw, H. M., Fuh, J. Y. H., Nee, A. Y. C., and Lu, L. (1999). "Formation of a new EDM electrode material using sintering techniques." *Journal of Materials Processing Technology* Vol. 89-90, pp. 182-186.

Zipperian, D. C. (2005). *Metallographic Specimen Preparation Basics*. Retrieved November 2nd 2012. From <http://www.metallographic.com/Technical/Basics.pdf> Vol.

Zwick, R. (2015). *Indentec Hardness Testing*. Retrieved April 1st 2015 from http://www.indentec.com/downloads/info_vickers_test.pdf



PTTA UTHM
PERPUSTAKAAN TUNKU TUN AMINAH